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Technology Development for Human Exploration beyond LEO in the New Millennium
IAA-13-3 Strategies & Plans for Human Mars Missions

Contact Author
William E. Larson
NASA/KSC, Mail Code: YA-D4
Kennedy Space Center, FL 32899
United States of America

Co-Authors
Dale E. Lueck and Clyde F. Parrish
NASA/KSC
Mail Code: YA-D2
Kennedy Space Center, FL 32899
United States of America

Gerald B. Sanders, Joseph R. Trevathan, R. Scott Baird and Tom Simon
NASA/JSC, Mail Code: EP4
Houston, TX 77058
United States of America

ABSTRACT

As we look forward into the new millennium, the extension of human presence beyond Low-Earth Orbit (LEO) looms large in the plans of NASA. The Agency's Strategic Plan specifically calls out the need to identify and develop technologies for 100 and 1000-day class missions beyond LEO. To meet the challenge of these extended duration missions, it is important that we learn how to utilize the indigenous resources available to us on extraterrestrial bodies. This concept, known as In-Situ Resource Utilization (ISRU) can greatly reduce the launch mass & cost of human missions while reducing the risk. These technologies may also pave the way for the commercial development of space.

While no specific target beyond LEO is identified in NASA's Strategic Plan, mission architecture studies have been on-going for the Moon, Mars, Near-Earth Asteroids and Earth/Moon & Earth/Sun Libration Points. As a result of these studies, the NASA Office of Space Flight (Code M) through the Johnson and Kennedy Space Centers, is leading the effort to develop ISRU technologies and systems to meet the current and future needs of human missions beyond LEO and on to Mars. This effort also receives support from the NASA Office of Biological and Physical Research (Code U), the Office of Space Science (Code S), and the Office of Aerospace Technology (Code R). This paper will present unique developments in the area of fuel and oxidizer production, breathing air production, water production, CO2 collection, separation of atmospheric gases, and gas liquefaction and storage. A technology overview will be provided for each topic along with the results achieved to date, future development plans, and the mission architectures that these technologies support.

INTRODUCTION

In NASA's Strategic Plan, it states that the mission for the Human Exploration & Development of Space (HEDS) Enterprise is to "expand the frontiers of space and knowledge by exploring, using, and enabling the development of space for human enterprise"[1]. To support this mission, Near (2000-05), Mid (2006-11), and Far-Term (2012+) Plans based on evolving mission durations and destinations have been created. While Near-term objectives only involve 14 day Shuttle and 30 to 90 day International Space Station (ISS) missions in Low Earth Orbit (LEO), Mid and Far term mission objectives are to expand human exploration beyond LEO. Mid-term objectives include 50 to 100 day lunar and libration point missions, and Far-term objectives include Near Earth Objects (NEO's) and lunar outpost missions (300 days) and Mars and main belt asteroid missions (1000 days).

Like the great explorers of the Earth, it is fundamental to any program of extended human presence and operation on extraterrestrial bodies that we learn how to utilize their indigenous resources. By pursuing the philosophy of "living off the land", also known as In-Situ Resource Utilization (ISRU), significant reductions in mission mass, cost, and risk are possible while also increasing mission flexibility and exploration capabilities, and enabling the long-term commercial development of space. Significant mass and cost reductions are possible by eliminating the need to launch everything from the Earth's surface. Mission risk is also significantly reduced by providing a functional backup to the life support system, reducing dependence on Earth supplied logistics, and increasing radiation protection using indigenous materials. ISRU can significantly enhance and expand robotic and human exploration mission flexibility and capabilities by increasing surface mobility through production of Extra Vehicular Activity (EVA) consumables, use of ISRU-supplied hoppers and fuel cell powered vehicles, and growth in outpost habitation and infrastructure (including electrical power). Lastly, development of ISRU capabilities can also enable the long-term commercial development of space by enabling low cost transportation, and providing the resources, technologies, and infrastructure required to allow commercial development activities to grow. The primary challenge for ISRU is to maximize the benefits of using space resources for cost and risk reduction, mission enhancement, self-sufficiency from Earth, and space commercialization in the shortest amount of time while minimizing Earth delivered consumables, equipment, and infrastructure.

A key area of ISRU that has significant early cost and risk reduction benefits while requiring minimum infrastructure is the production of mission critical consumables, such as rocket fuels, oxygen, water, and gases for life support, EVAs, and science, and fuel cell reagents and solar cells for power generation using resources available at the exploration site. ISRU can also enable the long-term commercial development of space by enabling low cost transportation, and providing the resources, technologies, and infrastructure required to allow commercial development activities to grow.

ISRU DEVELOPMENT & IMPLEMENTATION APPROACH

Development and implementation of space resource utilization is critical to achieving the mission objective of the HEDS Enterprise to "expand the frontiers of space and knowledge ...". To successfully meet this objective, ISRU processes and products must be beneficial, flexible, and affordable.

To be beneficial, ISRU processes and products must evolve from small and simple processes producing a limited number of high leverage products to large-scale initiatives with a wide range of products enabling self-sufficiency and independent growth from Earth. This approach provides immediate payback to initial investment and allows for a 'buy as you go' approach to space exploration and commercialization expansion. Mission critical consumables, such as propellants, life support gases, and power are the most logical and beneficial initial ISRU products. Numerous analytical studies have shown that in-situ production of propellants can significantly reduce initial and long term exploration launch masses and costs. Also, even with a 100% closed loop life support system, extensive lunar or Mars planetary surface exploration by EVA is not possible without in-situ production of oxygen.

To maximize the benefit of developing and implementing ISRU, the goals and objectives of initial processes and products should be common between two, if not all three, of the following initiatives: robotic/science exploration, human exploration, and commercial development of space. Common goals and objectives for all three initiatives include; increasing knowledge/understanding of resources and mission environments, successful sample/resource extraction, in-situ analysis/processing and sample/resource return to Earth, and enhancing or enabling missions through development and use of new concepts, such as in-situ production of propellants and other mission critical consumables.

Once humans leave Low Earth Orbit, there is a wide range of destinations of interest for exploration and commercial development, including Earth-Moon and Earth-Sun libration points, lunar surface and permanently shadowed polar regions, NEO and main belt asteroids, Mars and it's moons, and satellites orbiting Gas Giant planets (Europa, Titan, Ganymede, etc.). Each of these potential locations have different mission environments, available resources, and material/resource physical and chemical characteristics. Until actual mission destinations are specified, ISRU technologies and processes selected for development must be flexible in their ability to support multiple sites of exploration and commercialization. After examining potential exploration sites and their resources, a number of core ISRU 'building blocks' and common technologies were identified. These include fine-grained regolith excavation and refining, volatile furnaces and fluidized beds, atmospheric and volatile gas collection and separation, drilling, water & carbon monoxide/dioxide processing, and product liquefaction and long-term cryogenic storage. Fine-grained regolith is common to the top few meters of the moon, Mars, Phoboes/Deimos, and carbonaceous chondrite asteroids. Volatiles of interest include lunar solar wind volatiles (C, H2, He, & 3He), carbonaceous chondrite volatiles (H2O, N2, CO2, & SO2), and Mars regolith and potential lunar polar water. These common volatiles, along with atmospheric gases on Mars (CO2, N2, Ar), and the Gas Giant planets (H_2, He, ^3He, & CH_4) must be separated for immediate use or for further processing. Lastly, since production and storage of oxygen and propellants has been identified as the two most beneficial ISRU products initially, water and carbon monoxide/dioxide processing, and product liquefaction and long-term cryogenic storage needs are common for multiple destinations.

Finally, for development and implementation of ISRU to be successful, it must be affordable. To achieve this goal, a three-point development and implementation strategy has been initiated. One, ISRU technologies and processes developed initially should be common to more than one system (i.e. life support, power generation, etc.) or as mentioned above, common to multiple ISRU processes or sites of exploration. In most cases, a small reduction in performance from using a non-optimized solution can be offset greatly by the reduction in technology development costs and time. Two, ISRU technologies and processes should be applicable to Earth spin-off and/or space commercialization applications. For example, oxygen, water, and propellant production on the moon and in near-Earth space can be commercialized to supply these products for both government (NASA and DOD) and space industry applications. Three, to minimize costs and promote the use in other applications, ISRU technologies and systems should be developed in partnership with other government agencies, industry, and academia. With this in mind, the HEDS Technology/Commercialization Initiative (HTCI) was created, and Space Resources Development was one of six primary focus areas established in this program. This partnership must also extend to within NASA itself. For this reason, the HEDS Enterprise (Code M), through the Johnson and Kennedy Space Centers, is leading and coordinating the effort to develop ISRU with the NASA Biological and Physical Research Enterprise (Code U), the Space Science Enterprise (Code S), and the Aerospace Technology Enterprise (Code R). Examples of technology development coordination include life support and micro-gravity processing with Code U, small business innovative research and crosscutting technology with Code R, and Mars and outer-planet transportation systems with Code S.

ISRU PROCESS STUDIES

Lunar ISRU

Lunar exploration mission concept studies have typically concentrated on the production of products from regolith, trapped volatile, and potential polar ice resources. Relatively little attention has been paid to the resource acquisition end of the ISRU process and the practical aspects of lunar regolith excavation, drilling, and handling. To address this, JSC performed an initial study of lunar excavation and regolith handling to identify technical problem areas that will need to be addressed in future technology development programs. The technical problem areas identified stem from the unique micrometeoroid, pressure, temperature, radiation, gravity, dust, and soil conditions found on the lunar surface.

The micrometeoroid background environment will be a long-term issue for any exposed surfaces and thin walled structures such as tubing, struts, and closeouts. Equipment surfaces will be eroded over time. Hardware materials selection, protective covers, and maintenance are the primary considerations. Development of advanced, erosion resistant coatings are needed.

The pressure, temperature, and radiation environment effects are similar to those encountered on in-space missions and will require similar design and technology considerations. The large 44K to 384K (-229 to 110°C) temperature swing, the 14-day at a time exposure to each temperature extreme, and the high vacuum (10^{-9} to 10^{-12} torr) outgassing and vacuum welding potential inherent in the numerous mechanisms of lunar regolith excavation and handling equipment are of particular concern. All ISRU excavation and handling hardware developed will require rigorous lunar environment testing; although, no specific technology development targets were identified.

The reduced lunar gravity (0.165 g) will pose a challenge to the operations of lunar digging and drilling equipment. Terrestrial digging equipment is typically large and massive to take advantage of its weight for traction and digging forces. Lunar digging equipment will either need to be six times as massive as its terrestrial counterpart to have equivalent capabilities or find alternative ways to provide increased traction and digging forces. The transport of more massive digging equipment to the lunar surface is not practical. Descriptions of alternative reduced gravity digging methods and equipment are not yet abundant in the literature. Use of bulk regolith for increased ballast may be the only practical solution in the near term.

The lunar dust and soil will pose the biggest challenge for lunar regolith excavation and handling equipment. Lunar dust and soil does not experience the weathering seen by terrestrial and Martian materials. The result is that individual lunar soil and dust grains are very angular. This will have two potentially serious affects on lunar equipment. First, lunar dust is very abrasive and will pose a serious and continuing threat to joints, sliding surfaces, and seals. Second, the angularity of the lunar soil gives it anisotropic load bearing properties. It is much easier to sweep the upper layer of soil aside horizontally than to dig or drill down into the soil even a few centimeters. Vertical loading of the soil, even assisted by vibration, compacts the soil even further. Frozen lunar soil in permanently shadowed craters will likely be even harder to excavate. Lunar dust and soil also have interesting electrical properties. They are highly dielectric and can hold significant electric charge. This charge allows the dust to cling to almost any surface as was noted in the Apollo missions. This, combined with its inherent abrasiveness and small size (70μm average, 20% <20μm) will make the dust pervasive around lunar worksites. The effects on humans, unsealed electrical systems, and exposed mechanisms have not been quantified, but are expected to be serious. Methods of cleaning the dust off of surfaces and dealing with the effects of what dust gets past this cleaning will be significant development areas for both extended robotic and human lunar surface missions.

Mars ISRU

Mars exploration concept studies, unlike the lunar studies, have dealt with the entire atmosphere resource acquisition to product storage end-to-end system process concept internal details, but have not significantly addressed the potential Mars dust environment impacts or soil digging and excavation issues in much depth. To address this, JSC performed an initial study of potential Mars dust and soil characteristics that might impact ISRU plant operations to identify technical problem areas that will need to be addressed in future technology development programs.

The most serious technical problem areas identified for the dust are its chemical reactivity, general pervasiveness, and electrical discharge potential. The chemical constituents of the dust are not known with much certainty, but Viking test data showed it reacts very energetically when exposed to warm temperatures and water. No obvious corrosion has been observed to date, but this reactivity with water could impact water-generating processes, such as the Sabatier process, and will be a serious concern for human exposure. The pervasiveness of the dust has been observed to range from being suspended in violent storms that cover vast stretches of the surface for months to slowly obscuring photovoltaic cell arrays. Pathfinder experience was that the accumulation rate degraded power output of the array by 0.3% a day on average. The dry and low-pressure (7 torr) Mars surface conditions are very conducive to the buildup of electrostatic charges. Buildup of dust on and in electrical equipment could easily create direct shorting paths possibly causing power loss and equipment damage. Also, the combination of dust and the low-pressure atmosphere raises arching and corona discharge concerns.

Technologies and procedures to prevent or remove dust from surfaces and to neutralize its chemical and electrostatic effects will need to be developed to support long-term robotic and human surface missions. The Dust Accumulation and Repulsion Test (DART) portion of the Mars In-situ propellant production Precursor (MIP) flight demonstration was designed to further investigate the scope of the dust problem and to test methods of preventing this dust buildup[2]. Dust mitigation methods to be tested by DART include simple tilted surfaces (30°, 45°, and 60°), a low friction surface coating on a moderately tilted (30°) surface, and electrostatic repulsion concepts. These electrostatic repulsion methods pose a challenge. During development of the DART experiment, electrostatic discharge, as discussed earlier, was observed during a test to investigate the feasibility of electrostaticly removing dust that had already settled onto a solar cell. This led to the development of an experiment to electrostaticly repel Mars dust before it settles onto a solar cell instead of trying to remove it once it has settled. Another dust removal method that has been proposed, but not included in the MIP, would be to use compressed CO2 acquired from the atmosphere to physically blow dust off of surfaces. Originally manifested on the Mars 2001 Surveyor Lander, the MIP flight demonstration has been flight certified and is currently waiting to be manifested on a future Mars lander.

Knowledge of the soil characteristics is based solely on photographic evidence. Pathfinder observations suggest the soil at the Pathfinder site is similar to moderately dense soils on Earth, such as clayey silt with embedded sand and rocks. Soils elsewhere will vary but will likely have terrestrial counterparts. Therefore, the technologies required for Martian soil excavation and drilling should be similar to those needed for Earth with one exception. The reduced gravity (0.376 g) will require alternative ways to provide increased traction and digging forces similar those addressed in the previous lunar discussions.

PROCESS TECHNOLOGY & PRODUCTION OPTION DEVELOPMENT

Lunar Surface ISRU Technology & Production System Development

Extraction of volatiles from the lunar regolith has, until recently, predominately remained in the realm of studies. However, with the Lunar Prospector discovery of potentially significant concentrations of hydrogen/water in permanently shadowed areas of the lunar poles, there is renewed interest in developing the extraction technologies needed to take advantage of this resource. JSC has funded Lockheed-Martin Astronautics (LMA) and the Colorado School of Mines (CSM) to explore and define prototype technologies that will be needed for a small robotic system that can explore the harsh environment of a lunar polar cold trap for extended periods of time, locate promising deposits, excavate significant quantities of icy regolith, and extract water/hydrogen from this regolith. As part of this task, icy lunar regolith simulant will be prepared under lunar polar pressure and thermal conditions and its mechanical properties characterized. This information will then be used in defining the excavator design requirements. Completion of this icy regolith characterization is expected within the last quarter of 2001. Overall completion of this technology definition task is expected by the summer of 2002.

Direct use of the lunar regolith has also been the topic of many ISRU studies. The manufacture of photovoltaic cells from lunar materials is one of the more promising early ISRU applications. The University of Houston was awarded a grant through the Cross Enterprise Technology NASA Research Announcement process to refine and demonstrate the feasibility of producing silicon photovoltaic cells from simulated lunar materials under lunar environmental conditions of sufficient quality and potential quantity to be economically viable. This two-year project started in April 2001 and is currently working on the refinement of methods to extract silicon from lunar regolith; methane gas reduction and elemental carbon solid matrix reduction chemical processes. Later tasks include prototype cell and array manufacture in lunar vacuum conditions and the definition of a robotic silicon cell mass production and crawler system incorporating the demonstrated process.

Near Earth & Mars ISRU Technology & Production System Development

Since the production and storage of oxygen and propellants have been identified as the two most beneficial ISRU products initially, technology and system development for water and carbon monoxide/dioxide processing, and product liquefaction and long-term cryogenic storage needs are important core building blocks for ISRU systems for multiple applications and destinations. Work has started at JSC and KSC on characterizing and developing more advanced technologies to support on-orbit life support and Mars robotic missions.

Sabatier Reactor

Sabatier reactors catalytically convert H_2 and CO_2 into CH_4 and H_2O in a self-sustaining, exothermic reaction. When combined with the water electrolysis process, the integrated Sabatier/Water Electrolysis can be used for both propellant production and ISS and future human tended station life support system applications. Currently on the ISS, both H_2 (byproduct of water electrolysis from the production of breathing oxygen) and CO_2 (crew exhaled) are considered waste gases and are being vented to space. Using a Sabatier reactor would allow production of additional water from these consumables and in turn require that less water be transported to the ISS (~900 kg/yr), helping to decrease the cost of the permanently crewed space outpost. For propellant production, CO_2 acquired from the Martian atmosphere would be combined with H_2 from Earth (or electrolyzed from in-situ water) to allow production of CH_4 (fuel) and H_2O (which would be electrolyzed to produce O_2 and H_2).

An advanced Sabatier reactor has been designed, is being fabricated, and will be tested at JSC this year. The design (Figure 1) incorporates innovative features, such as regenerative preheating of the inlet H_2 and CO_2 gas flow in an attempt to better control the thermal profile along the length of the reactor. The reactor will be tested as a separate subsystem over a range of operating conditions (considering both life support and propellant production requirements) allowing optimization of the operating procedures and conditions. The reactor is designed to allow easy access to the internal components for configuration changes of the reactor. The reactor also has enhanced thermal data gathering features to better determine the internal thermal gradient down the axis of the reactor. The regenerative reactor configuration will be tested with the annular region empty, an annular metal foam insert, and helical fins in the annular region.

The reactor has been initially sized for a Mars robotic sample return mission that is also compliant with on-orbit life support system operating requirements. The range of testing parameters includes inlet flow rates of 50 g/hr to 250 g/hr of CO_2 at inlet pressures of 10 psia to 50 psia. Characterization testing of the reactor should be completed by late 2001. Future plans for this reactor are to integrate it into the next generation Sabatier/Water Electrolysis ISRU breadboard at JSC.

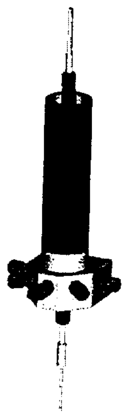

Figure 1: Regenerative Flow Sabatier Reactor

Water Electrolysis

Water electrolysis is the decomposition of water into hydrogen and oxygen by electric current. Since water is a key resource and product, water electrolysis is a critical technology in many ISRU processes and other space applications. In an effort to increase mass and power efficiency of future propellant production and life support systems, JSC procured from Hamilton Sundstrand and is currently testing a 3-cell liquid anode feed water electrolysis unit with an integrated H_2 & CH_4 separator. In a liquid anode feed cell, liquid water is circulated through the oxygen compartment. The liquid is present at the anode where the electrolysis takes place as protons, along with water, pass through the cell membrane. This method allows efficient heat removal and constant hydration of the membrane. The current density in liquid anode feed cells can be as much as ten times higher than in cathode feed cells, resulting in a smaller cell stack. The unit being tested is designed for a nominal O_2 production rate of 65 g/hr at a maximum pressure of 200 psia. This production rate, like the Sabatier reactor, corresponds to a Mars robotic sample return mission and again is also compliant with on-orbit life support system operating requirements.

The unit at JSC (see Figure 2) will be tested as a separate subsystem over a range of operating conditions to explore operating procedures and conditions. This subsystem includes valves, pumps, phase separators, and a deionization bed as well as instrumentation to give the operators as much control of and information from the test as possible. The ranges of operating conditions include inlet water flow of 500 cc/min to 700 cc/min at pressures of 14.7 psia to 200 psia and inlet temperatures of 5° C to 50° C. Characterization testing of the unit should be completed by late 2001. Future plans for this unit are to integrate it into the next generation Sabatier/Water Electrolysis ISRU breadboard.

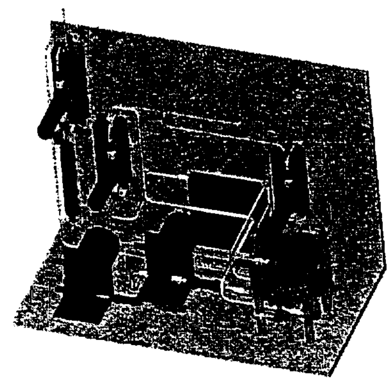

Figure 2. Water Electrolysis Unit Testing Configuration

Microchannel Thermochemical Reactors

Miniaturization of ISRU hardware in terms of mass and volume is essential to making ISRU practical for space flight applications. Towards this end, researchers at the Department of Energy's (DOE) Pacific Northwest National Laboratory (PNNL) under a multi-year CETDP funded effort managed through JSC are developing Microchannel Chemical/Thermal System (MCTS) technologies for Mars robotic ISRU and life support system scale applications. MCTS technologies use microchannel and etched-plate manufacturing techniques to fabricate miniature, essentially solid state reactors, heat exchangers, mixers, and separators[3]. These designs allow significant reductions in mass (70%), volume (80%), and power (50%) as well as rapid heat and mass transport, improved temperature and reaction kinetics control, and reduced gravity environment effects over conventional chemical processing system designs without a reduction in throughput.

Previously, single channel Reverse Water Gas Shift (RWGS) and Sabatier reactors had been built and tested to characterize the performance and reaction kinetics of microchannel reactors. This year, PNNL MCTS reactor work focused on developing single cell and multi-cell catalytic microchannel RWGS and Sabatier reactor units. The RWGS reactor work has looked at staged, single cell reactors. Testing was performed over the range of 500 to 700°C at H_2 to

CO_2 ratios of between 1 and 4. CO_2 conversion efficiencies as high as 80% were achieved with the first stage reactor. Overall conversion efficiencies were increased 14 to 19% more with addition of the second stage reactor. Conversion efficiency increased with increased temperature. At lower temperatures, coking occurred in the second stage reactor when the H_2 to CO_2 ratio approached stoichiometric. In short, the basic concepts and constraints were demonstrated. Based on these promising results and the lessons learned, multi-cell microchannel RWGS and Sabatier reactor concepts have been designed and fabrication of these reactors has begun. Initial manufacturing and pressure checks of the first multi-cell Sabatier reactor prototype unit look good. Testing of this initial Sabatier reactor is expected to start towards the end of the third quarter of 2001. Multi-cell RWGS unit testing is expected to begin in the fourth quarter of 2001

Atmospheric Constituent Collection And Separation

The first step in closed loop life support systems and Mars propellant production is the separation and acquisition of CO_2 from other gases. Since large amounts of CO_2 must be processed over extended periods of time on Mars (300 to 500 sols) for in-situ propellant and consumable production, a robust, and mass and power efficient process for acquiring and separating low pressure (0.1 to 0.15 psia) CO_2 from the Mars atmosphere and providing it at 15 to 75 psia for processing is required. There are four methods of Mars atmospheric CO_2 collection, separation, and conditioning currently under development: adsorption (gas/solid interaction), absorption (gas/liquid interaction), cryogenic separation (solidification), and mechanical compression. Based on previous trade study and breadboard test results, JSC recently focused on supporting the development of CO_2 acquisition through the use of a CO_2 solidification pump.

A CO_2 solidification pump requires active cooling to lower the atmospheric gas temperature in the pump to below 150 K (-123°C). At this temperature and at Mars pressures or easily obtainable on-orbit station and in-space vehicle life support system vent pressures, CO_2 will solidify. This frozen CO_2 can then be heated as needed to supply CO_2 at any desired pressure. The solidification pump is attractive as an acquisition concept for future human and Mars robotic missions as it allows smaller volume and higher pressure CO_2 delivery compared to most of the current adsorption pump designs and can simplify system design by sharing cryocooler hardware with the O_2/CH_4 liquefaction and storage systems. Because of this attractiveness, LMA is exploring thermal solidification as a means of acquiring and conditioning CO_2 from the Martian atmosphere as part of an activity funded through JSC. The initial program examined the major solidification pump subcomponents, such as the acquisition pressure vessel, circulation blower, and heat exchanger configurations as well as a variety of operating scenarios. The test results from the initial characterization program were very encouraging[4] (see Figure 3). A second-generation solidification pump is currently being fabricated based on the lessons learned. Testing of this second generation unit will be completed early in the fourth quarter of 2001.

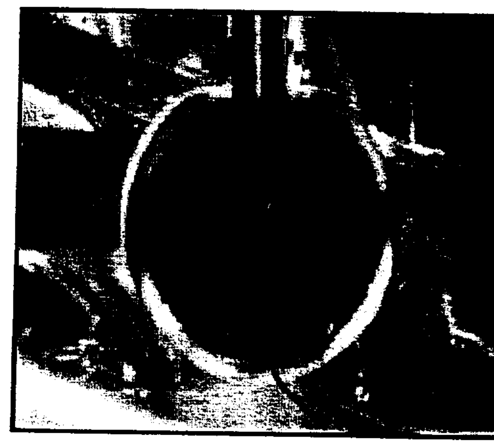

Figure 3: Solid CO_2 Growth on Cold Head

As stated earlier, miniaturization of ISRU hardware in terms of mass and volume is essential to making ISRU practical for space flight applications. This includes CO_2 acquisition sorption pump technologies. PNNL is exploring both microchannel thermochemical adsorption and absorption processes as part of their MCTS task with JSC. The microchannel absorber tests were conducted using polyethylene glycol (PEG) as a solvent for diethanolamine (DEA) over a temperature range of 25 to 80°C. The optimum CO_2 scrubbing temperature was determined to be about 50°C; although, this varied slightly with DEA concentration. Testing demonstrated the basic feasibility of the concept but also found that the microchannel gas absorption chemical solvent has a tendency to 'breakthrough' the contactor device into the gas stream. This will need to be addressed in future absorption pump designs before they become practical. The zeolite 13X based adsorber concept had previously been successfully demonstrated in single channel testing (see Figure 4). A second-generation, multi-channel, multi-cell, adsorption pump unit is now being designed. Its target CO_2 production rate will be >0.1 kg/hr with a compression ratio of >10:1 per stage for a 2 stage configuration. Each of eight cells will undergo staggered, 2-minute adsorb/desorb cycles to provide a continuous CO_2 output. Demonstration of efficient thermal recuperation between the cells will be a major goal of the test program. Testing is planned to start during the fourth quarter of 2001.

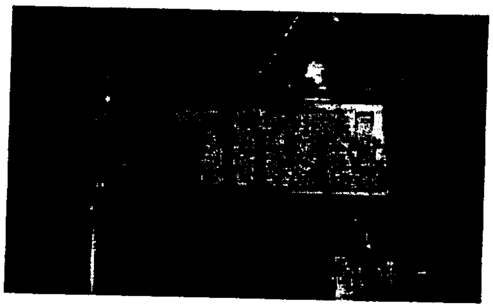

Figure 4: Single Channel Zeolite Adsorption Pump

Vapor/liquid separation; although, not used in Mars atmospheric CO_2 acquisition, will be useful for human life support system CO_2 collection as well as elsewhere in many other portions of the ISRU processing architecture. PNNL is also investigating microgravity compatible, microchannel vapor/liquid separator technologies. Several alternative single-channel condenser-phase separator configurations have been tested this year[5]. The results are very promising. Heat flux in excess of 60 kW/m^2, an overall heat transfer coefficient of 1000 W/m^2, and heat transfer effectiveness of 97% was demonstrated. Water recovery was 99% and phase separation was 100%. The next step will be to test a single microchannel, vapor/liquid separation device on the KC-135, Reduced Gravity Aircraft.

KSC has focused its effort on the acquisition and collection of N_2 and Ar from the Mars atmosphere using Hollow-Fiber Membranes (HFM). This technology could be used in conjunction with the CO_2 solidification approach mentioned above, to alleviate the build up of buffer gases that could occur inside the freezer if they are not removed. HMF gas separation has been studied in a number of industrial applications. Some of these applications include the removal of CO_2 from combustion processes [7,8]. However, most of these applications are at relatively high temperatures. No data is available on the HMF separation characteristics at the low temperatures encountered on the Martian surface. A research effort is currently underway at KSC to collect the required permeation data and design a prototype gas separation system. A testbed (Figure 5) has been constructed that allows various mixtures of CO_2, N_2, and Ar to be passes through HFM membranes at controlled temperatures that approach those found on Mars. KSC has found that decreasing the temperatures reduces the permeabilities of all gasses, but at different relative rates. The data that is being acquired will be used to design a gas separation system that could be used in concert with in-situ consumable

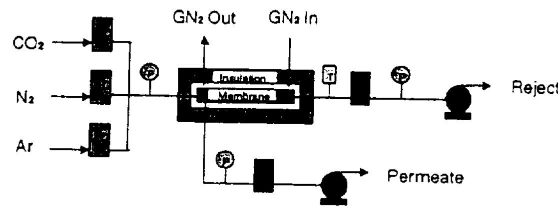

Figure 5. Hollow Fiber Membrane Testbed

production processes. The HMF separation system could be used in multiple configurations to meet mission needs. Figure 6 shows three possible configurations.

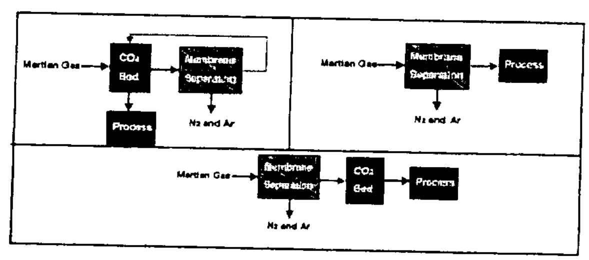

Figure 6. Configuration Options

RWGS and Alternate CO_2 Reduction

The Reverse Water Gas Shift (RWGS) process is another alternative for the production of consumables on the surface of Mars. This reaction has been well known since the mid-1800's. The RWGS reactor operates by taking H_2 and CO_2 (acquired from the Martian atmosphere) and combining them in an endothermic catalytic reaction (ΔH = +9 kcal/mole) to form H_2O and CO. The process uses a copper catylist and is seems to be most efficient at about 400 degrees C. The H_2O produced can be either stored for drinking or electrolyzed to produce O_2 and H_2. In the O_2 production operating mode, the H_2 is recovered and recirculated to the RWGS reactor and the O_2 is passed on to a cryocooler stage for liquefaction and storage. In this mode of operation, all of the H_2 can theoretically be reused if a method to recover it can be designed. Therefore only small amounts of H_2 or

H_2O would have to be imported from Earth to initiate and sustain the process.

Pioneer Astronautics performed initial research into the use of the RWGS for Mars oxygen production under a Phase I and II SBIR effort[6]. The main weakness that was identified as a result of this work was that the equilibrium constant of the RWGS reaction is fairly low. Each pass through the reactor only achieved about a 20% conversion efficiency. Therefore, a recycle loop was required to achieve full conversion of CO_2 and H_2 into H_2O. This requires the addition of a compressor and gas separatation stage that adds mass, complexity, and power requirements to the system.

Building upon the work of Pioneer Astronautics, the Kennedy Space Center has fabricated a testbed that will allow further development of RWGS technologies. The testbed is being used to further the understanding of the RWGS process, explore technologies to improve its efficiency, provide efficient gas seperation methodologies and to develop autonomous process control technology.

The testbed, shown in Figure 7, was tested this summer using a variety of operational parameters. In general, the system performed well and achieved H_2 conversions in the 98% range.

There are several areas where changes in the system design could provide improvements. In the current design, each pass through the reactor converts approximately 20% of the reactants. Therefore, a recycle system that separates the water and CO from the unreacted CO_2 and H_2 is required. The water is easily separated using a cold trap, but the CO separation is much more difficult. The testbed is currently using a commercially available hollow fiber membrane to separate the CO from the reactants. This membrane permeates CO_2 and H_2, but rejects the CO. However the permeation rates are driven by the partial pressures of the gases. This created a difficulty when we tried to increase the CO_2 concentration in an effort to scavenge more of the H_2 in the reactor. This lowered the partial pressure of H_2 in the reactor side of the recycle loop, resulting in faster permeation of the H_2 through the membrane. This tends to dampen out the attempts to adjust the reactant ratios. In the near term we plan to deactivate the recycle loop so that single pass conversion research on reactant rations and reaction temperatures can be conducted. Once we have a better understanding of the single pass coversion process we will study different hollow fiber membranes to find one that meets our needs. This is one of the more important areas of research as H2 losses are unacceptable since it must be imported from Earth.

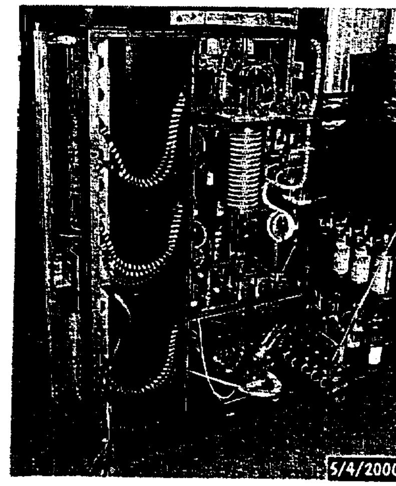

Figure 7. Reverse Water Gas Shift Testbed

The other problems encountered during testing are more of a system design issue. A small water pump was used to move water between the RWSG and H_2 cold traps. Activating this pump caused a momentary pressure drop in the system due to the volume being vacated by the water. This pressure drop perturbed the equilibrum of the system. Surprisingly, more than 30 minutes was required before the system returned to an operating equilibrum. A smaller pump that moves the water more slowly may resolve this problem.

Thermal management of the reactor also requires further study. The current system uses an external heater to raise the reactor temperature to about 400 degrees C. For an endothermic reaction, like RWGS, an internal heater would have been a more logical choice, but due to funding limitations we hoped that a less expensive external heater would meet our needs. Several concepts were tested to provide heat distribution through the bed. The operational data showed at least a 30 degree C temperature gradient across the bed. It is doubtful that this can be improved upon with a single heat source. Therefore, future systems must move towards a distributed internal heat source to improve overall reactor efficiency.

If the overall RWGS conversion ratio could be improved, then the need for a recycle loop, and it's aforementioned design difficulties could potentially be eliminated. This would be a great stride in making the RWGS process viable for extraterrestrial use. Two possible solutions to achieve this are the removal of either the CO or the H_2O at or near the moment of their creation within the reactor. Over the past year, KSC focused on methods to absorb the water molecules within the reactor. If this research proved successful, conversion efficiencies in excess of 90% could be anticipated without the need for a compressor and separator recycle loop.

Initial efforts were to build a desiccant electrolysis cell that would capture the water, electorlize it, and return the H2 to the reactor. A prototype cell was constructed using phosphorus pentoxide as the desiccant. Laboratory tests showed that the prototype did work, however it did not meet the needs of the RWGS. The cell chemistry would have released O_2 back into the reactor rather than H_2, as was desired. While this has proved to be a deadend for RWGS improvements, it does offer a continuously regenerable technology for drying O_2 gas streams as they exit water electrolysis units. When resources become avaialbe, KSC will begin to investigate whether a practical method of removing the CO from the reactor can be developed.

KSC is also investigating other possible CO_2 reactions that would result in oxygen production. These technologies are at a much lower technology readiness level, but are being pursued to understand their strengths and weaknesses. The technologies being investigated are: molten carbonate electrolysis, non-aqueous electrolysis of carbon dioxide, ionic liquid electrolysis, liquid carbon dioxide electrolysis, and lower temperature mobile oxide ceramics.

Molten Carbonate electrolysis cells have been proposed and developed in the past for CO_2 scrubbing from spacecraft cabin air as early as 1965. These early designs formed a carbon cake in the molten salt bath, which had to be removed and replaced to keep the process operational. This would be unacceptable for an autonomous O_2 production system on the surface of Mars. However, using a different cathode reaction, CO can be formed, eliminating the solid waste product problem. This process operates at a lower temperature than Zirconia Electrolysis and a considerably lower cell voltage. The cell voltage of 0.75 volts produces oxygen at about half the input power of a zirconia cell. The lower cell temperature should yield further savings, as well as a more rugged assembly for launch and landing.

Another possible alternative to produce O_2 from CO_2 is non-aqueous electrolysis. In electrolysis, the potential limits of an electrode are established, in part, by the limits of oxidation and reduction of the solvent and electrolyte system used. In aqueous systems, the limits are set by the reduction and oxidation of H_2O to produce H_2 and O_2, respectively. The reduction of CO_2, in general, proceeds at a more cathodic potential than for the reduction of H_2O to H_2. Although varying the electrode material to obtain a favorable overpotential difference between these two reductions is possible, the elimination of H_2O from the solvent system employed can eliminate the possibility of a competing H_2O reduction completely. Besides the molten salt electrolysis, which is also a non-aqueous system, there are several solvent systems that have been used with much wider electrochemical windows (the potentials between anodic and cathodic breakdown of the solvent) that could be employed to easily reduce CO_2. Other properties, which are important, are the dielectric constant of the solvent and its polarity. These two characteristics determine the solvent's ability to dissolve and ionize a suitable electrolyte. We have evaluated three solvents for their ability to reduce CO_2: acetonitrile, dimethylsulfoxide, and propylene carbonate. These solvents were chosen for their wide electrochemical windows that allow the reduction of CO_2 without interference from electrolytic breakdown of the solvent. These solvents do not produce solutions with high concentrations of ionized electrolytes and they can operate at low temperatures where liquid CO_2 can exist. They are highly soluble with liquid CO_2 and therefore can produce conductive solutions that have very high molar concentrations of CO_2 and therefore could lead to an efficient CO_2 electrolysis system. While CO_2 reduction was observed in each of these solvents, the products of this reduction did not produce oxygen at the anode. The solubility of either carbonate or oxide ions in these solvents (ions that could be expected to produce oxygen at the anode) are very low. Current capacity for the experimental cells constructed was also very low, in keeping with the poor solubility of viable anode precursors.

Ionic liquids are compounds that are composed entirely of ions, such as the molten salts described above. However, not all ionic liquids require high temperatures to exist in the liquid phase. In fact, a large number of these materials are liquid at room temperature. The potential advantage of these room temperature ionic liquids (RTIL) is obvious, i.e., since they are liquid at room temperature, they do not require the power needed to melt the molten carbonates. Typical examples of RTILs are N-alkyl-pyridinium and 1-alkyl-3-methlyimidazolium salts, and alkylated thiazolium salts, and amide melts with nitrates. In addition, these materials have been found to have large electrochemical windows. Work is underway at KSC to use these RTILs to dissolve compounds, such as carbonates or oxides, and attempt to duplicate the electrolysis of molten carbonates at lower temperatures. RTIL may provide an alternate to the non-aqueous solvent studies, which require the addition of an electrolyte to provide electrical conductivity. Therefore, the potential advantages of RTIL will be explored with the hope of eliminating high-temperature operations and complex solvent mixtures while retaining high conductivity. We are working with Prof. Robin Rogers at the University of Alabama to design and synthesize suitable ionic liquids for the construction of CO_2 electrolysis cells.

Liquid CO_2 is a fine solvent for many applications. However, it is not very useful as a solvent for electrolytic processes. The very low dielectric constant does not allow ionization of any suitable electrolyte. Yet there are significant advantages to using liquid CO_2 as a component of any electrolysis cell. As the primary input reactant to a Mars O_2 generator, it is desirable to achieve as high a concentration of CO_2 at the cathode as possible. Using a typical porous electrode for gas introduction into an electrolysis cell would require a high tech construction and material. This type of technology took many years to develop successfully for use in aqueous systems. In a CO_2 system, these electrodes must retain the solvent through surface tension while maximizing the area of contact between the electrode, a thin film of the electrolyte, and the input gas stream. The production of a gaseous product ($2\ CO_2 \leftrightarrow 2\ CO + O_2$) only complicates the design problem by creating a diffusion barrier of nonreactant gases at the electrode. Such electrodes utilize only a small fraction of the potential electrode area due to the requirement for three phase contact at the electroactive sites. This can be largely overcome and the electrodes simplified to a standard metal surface by dissolving the reactant CO_2 in the solvent system. Fortunately, CO_2 is an excellent co-solvent and it is highly soluble or miscible with the aprotic solvents under consideration for use in the ionic liquid systems mentioned above. This allows concentrations of 5 Molar or more to be achieved in solution, instead of 0.04 M/L for pure CO_2 gas, or even lower concentrations for gas bubbled through the solvent. Using a solvent system with high CO_2 solubility allows the pressurization of the electrolysis vessel to achieve CO_2 concentrations in the electrolyte that vary from milli-molar to multi-molar concentrations, as long as the temperature is below the critical temperature for CO_2 (30.98°C). This provides great flexibility in optimizing the current density and reduction rate in these cells. It also creates a problem of separating any gaseous products of the cell from the feed CO_2. For the cathode reduction of CO_2, it is possible to form solid carbon ($CO_2 \leftrightarrow C + O_2$), instead of CO as mentioned previously, and thereby eliminate the gas separation problem at this electrode. Carbon formation in the much lower temperature ionic liquids would be more feasible to handle than in a molten carbonate cell. Experiments on CO_2 cosolvents with the nonaqueous solvents mentioned above did confirm larger reduction currents with higher CO_2 concentrations, but the lack of a suitable oxygen producing anode reaction is still the limiting factor. We anticipate that the ionic liquids will overcome this limitation.

The O_2 product stream can be separated from CO_2 in a post-processing step, recycling the CO_2 back into the electrolysis cell using Hollow Fiber Membranes. These membranes will be discussed in more detail in the following section

Mobile oxide ceramics allow the transport of oxide ions within the ceramic matrix at elevated temperatures. Yittria stabilized zirconia (YSZ) is one such ceramic. Similar ceramics have been fabricated that operate at a much lower temperature, about 500° C versus 800° C or higher for YSZ. These ceramics have been shown to reduce NOX and can probably reduce CO_2 as well. We have funded Prof. Eric Wachsman at the University of Florida to demonstrate this capability and establish the operating characteristics of such a system. The lower temperatures would allow the use of metals in the manifold construction of the electrolytic cell. This would lead to a considerable improvement in ruggedness and shock resistance over existing YSZ based systems where an all ceramic construction has been necessary in the high temperature zone.

Surface Product & Cryogenic Liquefaction And Storage

Reliable, low power, and mass efficient cryogenic storage of product fluids, such as O2, CH4, and N2 are essential for the successful incorporation of ISRU into future planetary missions and as a way to leverage cryogenic propellants for future bases, depots, and in-space vehicles. Most of the recent efforts in this area have focused on the liquefaction and storage of oxygen and methane as cryogenic fluids down to the 77 Kelvin range. With these applications in mind, JSC has been sponsoring the investigation and development of several promising cryocooler technologies through the SBIR program and an interesting cryogenic storage concept through Code M funding. Currently this includes pulse tube, turbo-Brayton, and split Joule-Thomson thermodynamic cycle cryocooler technologies and a common bulkhead O2/CH4 storage tank concept.

A pulse tube oxygen liquefier has recently been completed by Mesoscopic Devices, LLC. This cooler has a design point of 14.5 W of cooling with an input power of 152 W at a temperature of 90 K with a rejection temperature of 245 K (Mars ambient). The completed unit will be used in integrated testing with the advanced common bulkhead O2/CH4 cryogen storage tank at LMA as part of an ongoing ISRU effort. Cryocoolers of this cooling capacity are directly applicable to robotic scale ISRU propellant production missions, rover fuel cell reactant storage, and supplemental cooling applications for larger missions.

Mesoscopic Devices, LLC is also involved in the early stages of developing a turbo-Brayton oxygen liquefier/cooler. This unit will be designed to supply 100 to 5,000 Watts of cooling at 90 K at a rejection temperature of 245 K (Mars ambient). This mid to large-capacity cryocooler will be adequate for human scale ISRU activities and cover both O2 and CH4 liquefaction and storage for both ascent propulsion and life support needs. The turbo-Brayton cycle is the current thermal cycle of choice for these mid to large-capacity missions because of its scalability and high potential efficiency.

Creare is developing a split Joule-Thomson (JT) cycle oxygen liquefier/cooler. This cooler/liquefier design is sized for low to mid-capacity ISRU applications such as ascent propulsion and robotic or small-scale human surface mission needs as well as in-space vehicle and depot applications. The design specifications are 41 W of cooling at 90 K with an input electrical power of 280 W at a rejection temperature of 300 K. At the Mars ambient temperature of 245 K, the cryocooler will need substantially less input power.

Future needs for cryocooler development will be focused on hydrogen cryocoolers as hydrogen is the most common Earth supplied reagent used in ISRU processes. It is also one of the more difficult fluids to liquefy and store. Liquid hydrogen at ambient pressure has a temperature of 22 Kelvin. This is an extreme temperature requirement that current state-of-the-art cryocoolers cannot perform in anything close to an efficient manner; however, recent advances in cryocooler technology in operating life, heat-lift capability, and power efficiency are promising. The applications for hydrogen cryocoolers will range from planetary surface ISRU hydrogen storage and possibly liquefaction, to the long-term maintenance of liquid hydrogen for propulsion and power systems for in-space vehicles. First cut cooling requirements for these advanced state-of-the-art hydrogen coolers/liquefiers will be on the order of 15 to 40 Watts of cooling at 22 Kelvin with a rejection temperature of between 300 K and 245 K with efficiency targets in the range of 20 to 40 Watts of input power per Watt of cooling.

LMA has designed and is fabricating a prototype LO2/LCH4 common bulkhead cryogenic storage tank. The tank is designed to store a total of 15kg of propellants of which 3.5kg will be the CH4. The tank will be ASME certified for a maximum operating pressure of 500 psia and will be capable of operating in terrestrial and Mars environmental conditions. The target storage temperature is 115K. Characterization testing is expected to start by October 2001 and expected to last through the end of the year depending on the challenges encountered.

Technical challenges must also be addressed in the area of cryogenic insulation. While significant research has been performed on insulation in the earth's atmosphere and in the vacuum of space, relatively little work has been done in the "soft vacuum" pressures of Mars. Over the last two years the Cyrogenics Testbed at KSC has been conducting tests on insulation materials for Mars applications. The tests have been conducted with liquid N_2 dewars in a CO_2 atmosphere at Martian pressures. This pressure region is very dynamic because radiation, gas conduction and convection, and solid conduction are all significant contributors to the overall heat leak. Test articles have included combinations of aluminum foil, fiberglass paper, polyester fabric, silica aerogel composite blanket, fumed silica, silica aerogel powder, and syntacic foam.[9] The test results to date have shown a large performance variation in this environment. However, aerogel based insulations seem to hold significant promise to meet the needs of lightweight and robust cryogenic storage on Mars. Its low mass and impressive performance make it an ideal candidate for Mars missions where total system mass will be a significant cost driver.

KSC is also conducting research into the design of H_2O storage systems for Mars. If H_2O is produced on the surface of Mars via one of the ISRU processes mentioned previously, then this H_2O must be efficiently stored for long periods prior to the crew's arrival. Storing the H_2O in tanks carried to the surface would again add mass to the overall system and require energy to keep it from freezing. However, taking advantage of the low temperatures on Mars, it may be possible to store the water in solid form on the surface. These "logs" of water could then be melted and used as need by the astronauts upon their arrival. If funding becomes available this Fiscal

Year, KSC plans to build a prototype of such a system to prove its feasibility.

RATIONALE & STRATEGY FOR ISRU DEVELOPMENT AND FLIGHT DEMONSTRATIONS

ISRU flight demonstrations and missions which incorporate ISRU are a key aspect in the ISRU Strategic Plan. There are four main reasons to perform ISRU flight demonstrations and incorporate ISRU into future robotic and human space missions:

1) Increase knowledge of the potential resources and mission environments
2) Increase confidence in ISRU technologies for use in future human missions
3) Enhance and/or enable space science, human exploration, and/or commercial development of space
4) Engage and excite the public

Combined science and ISRU demonstration missions are required to eliminate uncertainties in mission environments and for future ISRU applications where knowledge of the resource of interest is uncertain, such as water concentrations in Mars regolith, lunar polar regions, and asteroids. This is especially important to foster and promote commercial space activities based on space resources. To increase investor confidence and minimize risk, joint science, HEDS, and commercial missions for prospecting and resource extraction are recommended to insure the desired resource or product can be economically extracted and processed in quantities necessary for commercial success. Demonstration missions also lower the risk and increase confidence in use of ISRU in human missions in two areas. One, Earth based testing alone can not fully or adequately simulate all mission environments, such as Mars dust/wind and reduced gravity, on Earth for long periods of time. Two, the confidence in use of ISRU in future human missions is significantly increased by demonstrating operation and performance of critical ISRU technologies and systems in relevant human mission situations. By progressively flying more complex ISRU demonstrations, the development, schedule, cost, and mission risks are minimized. This is extremely important for human exploration and the commercial development of space. As mentioned previously, missions that incorporate ISRU can significantly enhance or enable scientific and human exploration by increasing mission scope, flexibility, or duration, and the commercialization of space by providing the necessary products, raw materials, capabilities, and infrastructure. Lastly, the use of in-situ resources supports the American pioneer spirit of exploration by "living off the land", and it demonstrates to the public that NASA is serious about human exploration and settlement of our solar system.

A significant gap exists between analytical studies and reliance on technologies for mission critical events, such as ISRU. As this paper highlighted, there are currently Earth-based laboratory-scale tests and demonstrations underway to advance critical elements of ISRU. Because of the cost and risk of human exploration, ground and flight validation is required. To maximize the benefits to both the Space Science and HEDS Enterprises, an evolutionary mission incorporation strategy is recommended. The proposed strategy evolves ISRU size and usage in the following program and exploration phases:

- Phase I: Joint resource and environment science and ISRU demonstrations not critical to science mission success.
- Phase II: Extended mission/surface science investigation and exploration based on ISRU supplied products
- Phase III: Enhanced or enabled robotic exploration based on ISRU
- Phase IV: Enhanced or enabled human exploration based on ISRU

Examples of Phase I missions include the Mars In-situ propellant production Precursor (MIP) flight experiment, which combines the demonstration of key ISPP technologies with characterization of the Mars environment and dust, and the excavation and processing of Mars regolith for volatiles and water. Examples of Phase II missions include collecting argon or other gases to extend science instrument life or drilling operations, and producing explosives for excavation or seismic activities after Earth supplied gases and explosives are exhausted. Another Phase II mission concept is the production of propellants to enable a lander to hop to another location after initial science goals have been met at the first location, thereby extending the mission and the science obtained. Examples of Phase III missions include Mars ISPP sample return, fuel cell power rover, and deep drilling missions.

Potential Future ISRU Flight Demonstrations

Long-term and extensive ground testing of ISRU technologies and systems under simulated mission environmental conditions is key to enabling the incorporation of ISRU into future robotic and human exploration missions and the commercialization of space. However, as has been previously mentioned, without actual flight demonstrations, mission planners and commercial investors will continue to perceive the incorporation of ISRU into a mission as either high risk or not worth the potential benefits, even though other systems (such as life support and fuel cell power generation and storage) utilize similar technology and hardware. It is the goal of both the ISRU Strategic Plan and the HEDS Technology & Commercialization Initiative to combine the needs and capabilities of the Space Science Enterprise, HEDS Enterprise, and the commericialization of space to minimize the cost and risk of future ISRU related activities, and to verify potential resources and demonstrate extraction viability. Besides a Mars ISPP sample return mission, possible near-term flight demonstrations that have been identified that meet these common needs and capabilities include:

- Lunar Polar H_2/H_2O Mission – to obtain information for further scientific understanding of the moon and it's history, and to verify the presence and extent of water resources on the moon and demonstrate extraction of this resource. Information from this mission would have a significant impact on future human exploration and commercial initiatives on the moon.
- Near Earth Asteroid/Extinct Comet Prospector Mission – to obtain information for further scientific understanding of Near Earth Objects (NEO's) and the history of the solar system, and to determine potential NEO resources and the ability to economically extract them. Since large amounts of carbon, rare Earth elements, and possibly water are not readily available on the Moon, NEOs may be critical for future large-scale in-space manufacturing and construction efforts.
- Mars Surface Water & Deep Drilling Mission – to increase scientific understanding of Mars surface and subsurface mineralogy and composition while demonstrating the extraction of water which is critical for long term self-sufficiency on the Mars surface. Robust and autonomous deep drilling technologies may be applicable to terrestial oil drilling, so commercial technology spin-in and spin-off activities are possible
- Mars Fuel Cell Rover Mission – to provide around-the-clock rover operations with high power scientific instruments and drills, while demonstrating critical HEDS technologies and systems under relevant mission environments. Since the same technologies may be applicable to fuel cell powered automobiles and portable power generation units, Earth spin-off commercial activities are possible.

CONCLUSIONS & SUMMARY

Numerous analytical studies have been performed over the past several decades that all show ISRU can significantly reduce the mission mass, cost, and risk of both robotic and human exploration missions. It is clear after examining the benefits and potential applications, that the development of ISRU is key for both long-term human exploration of our solar system and to the long-term commercialization of Space. A significant gap exists between analytical studies and reliance on technologies for mission critical events, such as ISRU. As this paper highlighted, there are currently Earth-based laboratory-scale tests and demonstrations underway to advance critical elements of ISRU. However, because of the cost and risk of human exploration, further ground and flight validation is required. An evolutionary ISRU mission incorporation and phasing strategy is recommended to combine the needs, goals, and objectives of the Space Science and HEDS Enterprises with the commercial development of space. Until this is done, mission planners and commercial investors will continue to perceive the incorporation of ISRU into a mission as either too high of a risk or not worth the potential benefits, even though other critical systems utilize similar technology and hardware.

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It should be noted, that the purpose of some of the references made in this paper is to provide the reader with further information on the subject discussed, and should not be considered as all inclusive or as an endorsement for any one particular concept or organization.

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